Solar Neutrinos Planets, and SNO+

- Solar formation and evolution: the Standard Solar Model
- The photospheric absorption line - helioseismology conflict
- Metal segregation: the protoplanetary disk and solar convective zone
- SNO+ as a tool for probing the solar interior

Wick Haxton: NSD Monday Meeting 11 January 2010

The Standard Solar Model

- Designed to reproduce the basic evolutionary features of low-mass hydrogen-burning stars
  - ◇ local hydrostatic equilibrium: gas pressure gradient counteracting gravitational force
  - ◇ hydrogen burning, dominated by the pp chain
  - ◇ energy transport by radiation (interior) and convection (envelope)
  - ◇ boundary conditions: today's mass, radius, luminosity; the ZAMS abundance ratios H:He:Z needed

- The implementation of this physics requires
  - ◇ electron gas EOS, which under solar conditions is quite close to that of an ideal gas
  - ◇ low-energy nuclear cross sections for the pp chain and CN-cycle
  - ◇ an initial composition: solar metals play a major role in determining the Sun's opacity (free ↔ bound transitions)

Composition/metalicity in the SSM

- Standard picture of pre-solar contraction, evolution
  - ◇ sun forms from a contracting primordial gas cloud
  - ◇ passes through the Hayashi phase: cool, highly opaque, large temperature gradients, slowly contracting ↔ convective (mixed)
  - ◇ radiative transport becomes more efficient at star's center: radiative core grows from the center outward
  - ◇ ZAMS: thermonuclear energy generation compensates emissions

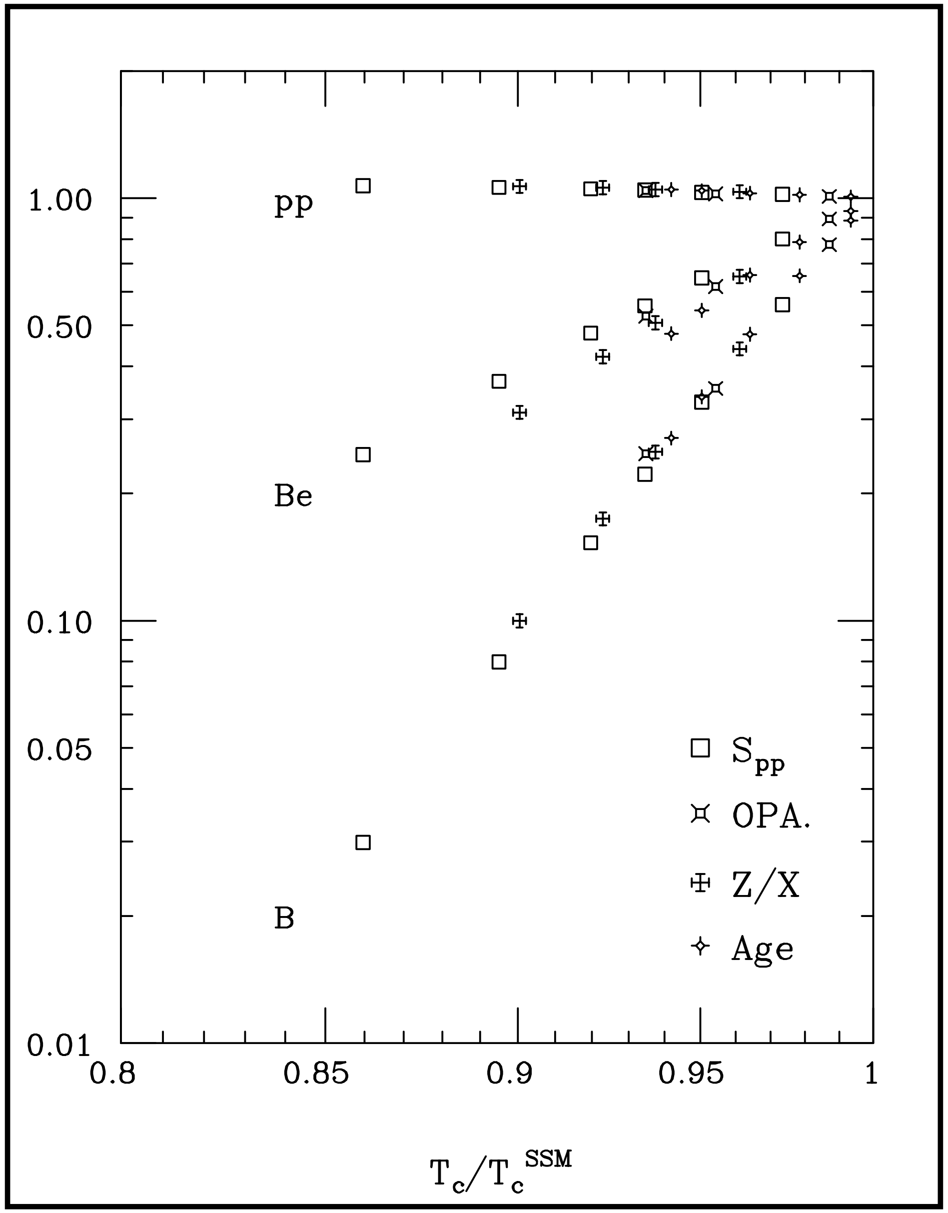
- The SSM assumes that, because the Hayashi phase fully mixed the sun, the radiative and convective zones will be chemically identical
  - ◇ as H+He+Z=1, two conditions needed to fix ZAMS composition
  - ◇ Z fixed to contemporary abundances: volatile elements from photospheric absorption lines; others from meteoritic abundances, assumed representative the primordial gas
  - ◇ H/He fixed by condition that luminosity reproduced at 4.6 b.y.

Model tests:

- Solar neutrinos: direct measure of core temperature to ~ 0.5%
    - ◇ but Davis's quest to make this measurement was de-railed for ~ 30 years by the solar ν problem

- Helioseismology: inversions map out the local sound speed
    - ◇ prior to 2000, the SSM - helioseismology concordance was considered a significant confirmation on the model
    - ◇ acoustic modes sensitive to the depth of the convective zone and surface He abundance

ν fluxes track with core T -- regardless of the kind of SSM perturbation -- up to small corrections primarily due to the finite core size



Castellani et al.

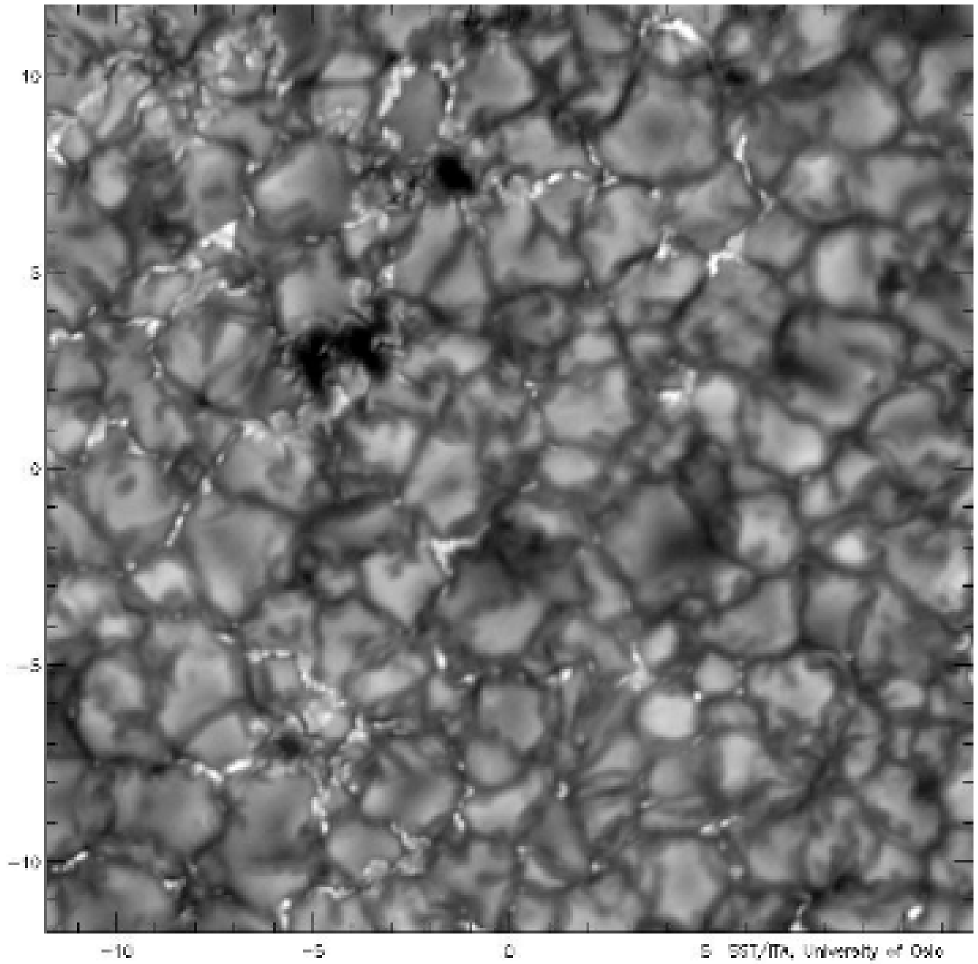
Recent Re-evaluations of Photospheric Abundances

- SSM requires as input an estimate of core metalicity at t=0
- Taken from meteoritic abundances or from photospheric absorption lines: the latter are the only practical way to determine the abundances of volatile heavy elements, such as C, N, O, Ne, Ar
  -- SSM then assumes a homogeneous zero-age sun characterized by these abundances, for reasons previously described
- These metals influence solar dynamics: free-bound transitions important to opacity, influencing local sound speed: different metals dominate in different solar regions
- The once excellent agreement between SSM and helioseismology due in part to this input (Grevesse & Sauval 1998)

- The classic analyses modeled the photosphere in 1D, despite stratification, velocities, inhomogenieties

- But new 3D, parameter-free methods have been introduced, significantly improving consistency of line analyses

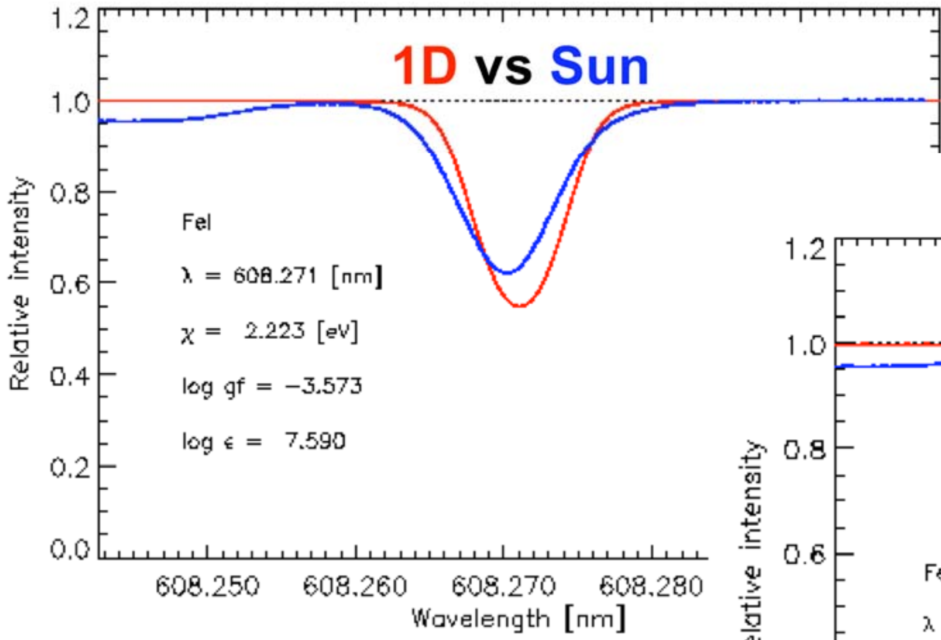
Dynamic and 3D due to convection

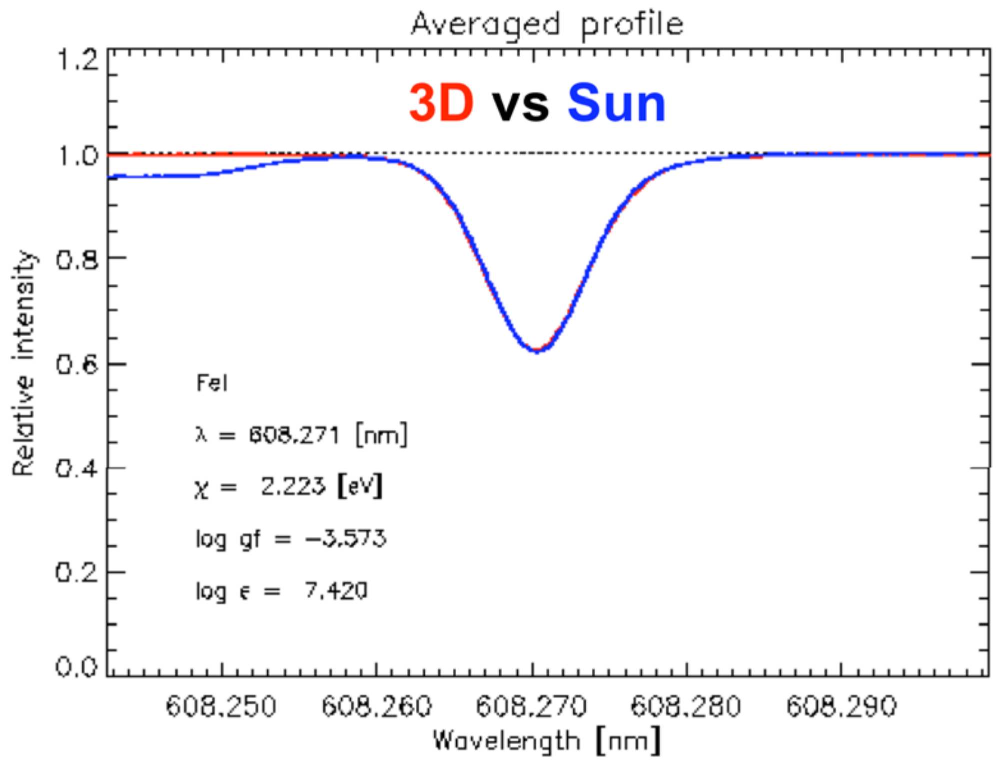


Mats Carlsson (Oslo)

Sun

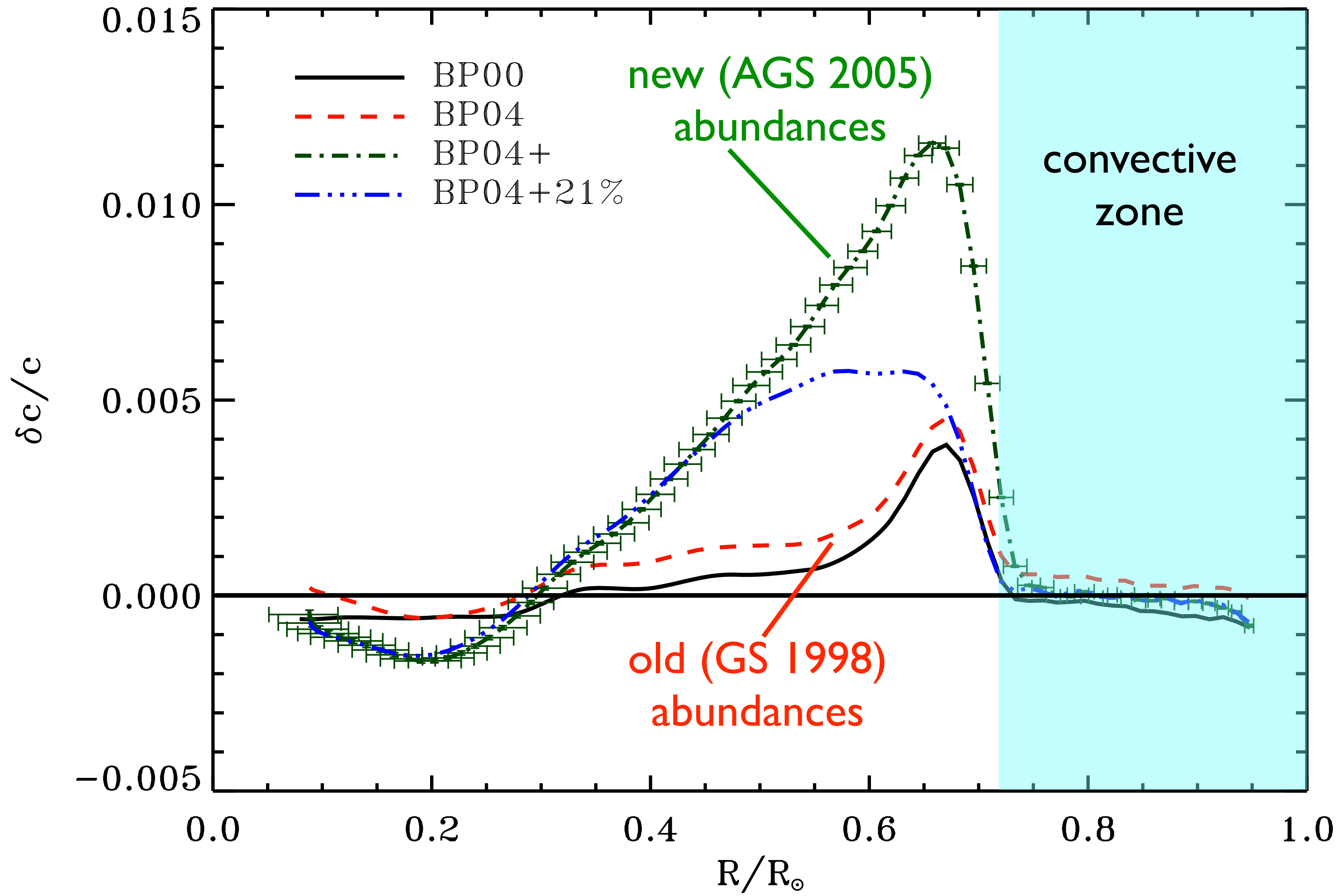
Averaged line profiles (from Asplund 2007)





- Spread in abundances from different C, O lines sources reduced from ~ 40% to 10%
- But abundances significantly reduced Z: 0.0169 ⇒ 0.0122
- Makes sun more consistent with similar stars in local neighborhood
- Lowers SSM ^{8}B flux by 20%

But the consequences for helioseismology were upsetting

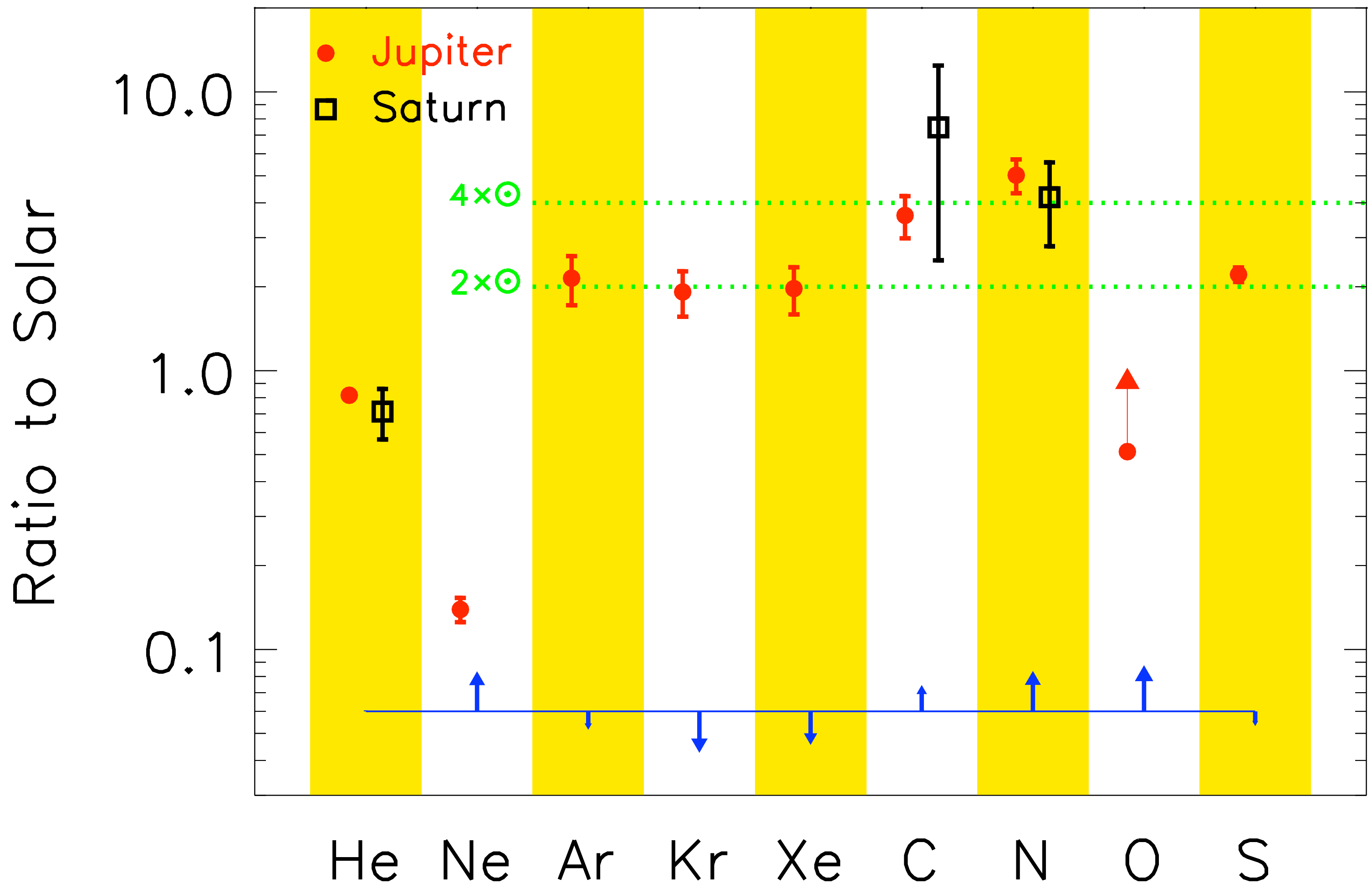


Bahcall, Basu, Pinsonneault, Serenelli 2004

- Discrepancy largest for $T \sim 2\text{-}5 \times 10^6$ K: C, N, O, Ne, and Ar are partially ionized, with O and Ne particularly important to the opacity
- Troubling because the previous concordance between the SSM and helioseismology helped establish the credibility of the SSM

Metals and the Proto-planetary Disk

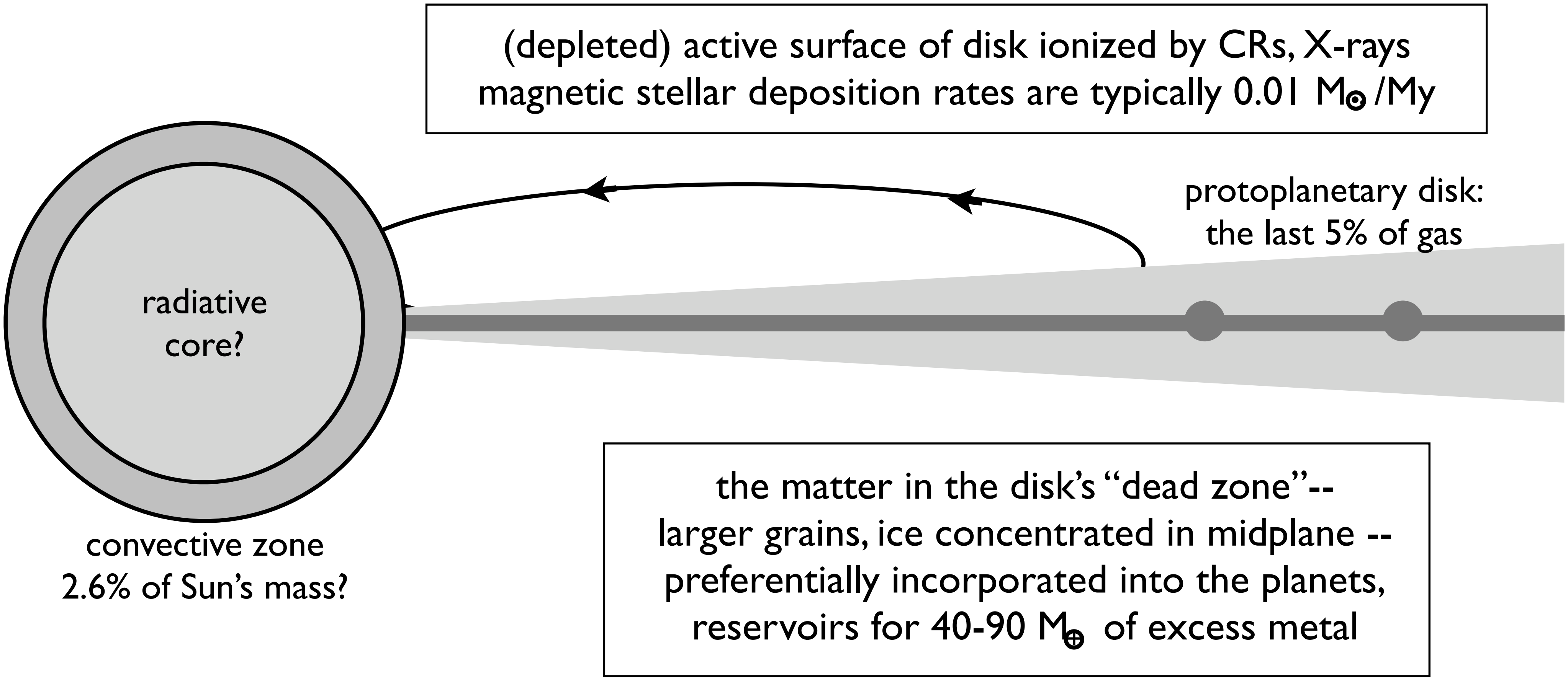
- Accept the photospheric and helioseismic results at face value: the convective zone (3% of the sun's mass) has a lower metal content than the radiative zone: deficit in the convective zone is 50 $M_\oplus$
- Galileo, Cassini, and subsequent planetary modeling show that significant metal differentiation occurred late in the evolution of the solar system, associated with formation of the gaseous giants
  - ◇ planets form late, involving the last ~ 5% of the gas
  - ◇ angular momentum transfer: that gas is in a thin disk
  - ◇ metal-rich grains and ice collect at the disk midplane
  - ◇ formation of the 10 $M_\oplus$ rock cores of the giant planet, which scour out this enriched material
  - ◇ rapid (1-few My) formation of gaseous envelopes, after the bulk of the nebular gas has already dissipated (Bodenheimer and Lin 2002)
  - ◇ timing: the sun already has developed its radiative core
- The observed atmospheric enrichments indicate a total metal excess of (40-90) $M_\oplus$, depending on planetary modeling uncertainties (Guillot 2005)



Galileo data, from Guillot AREPS 2005

Standard interpretation: late-stage planetary formation in a chemically evolved disk over ~ 1 m.y. time scale

A speculation: a single mechanism perturbs and segregates the last few percent of nebular gas, resulting in the enrichment of planetary atmospheres and dilution of the convective zone



The sun's deep interior would reflect the composition of the primordial gas cloud; the planets and solar surface would be processed

What can we do beyond idle speculation?

- *Phenomenology*: model the hypothesized gas deposition to determine, e.g., the helioseismological signature of such deposition

- *Numerical simulations*: try to start on the daunting task of building a standard solar system model, following gas cloud collapse, proto-solar evolution, disk formation, disk astro-chemistry, and planetary formation: integrate many separately challenging tasks, such as stellar formation, planetary evolution, and astrobiology

- *Observations*: one can study solar twins -- do patterns emerge when the surface abundances of solar-like stars, with and without planets, and with varying convective envelope depths? (in progress)

- *Measurement*: find a way to determine the metal content of the solar core -- the outstanding opportunity is SNO+

Solar neutrino tests: 99% of the Sun's energy comes from the pp chain; the best known ν flux, the ^{8}B branch, varies as ~ T^{22}

$$p + p \rightarrow {}^{2}H + e^{+} \boxed{+ \nu_e} \qquad p + e^{-} + p \rightarrow {}^{2}H + \nu_e$$

99.76% 0.24%

$${}^{2}H + p \rightarrow {}^{3}He + \gamma$$

83.2% 16.7%

$${}^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p \qquad {}^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$$

99.88% 0.12%

$${}^{7}Be + e^{-} \rightarrow {}^{7}Li \boxed{+ \nu_e} \qquad {}^{7}Be + p \rightarrow {}^{8}B + \gamma$$

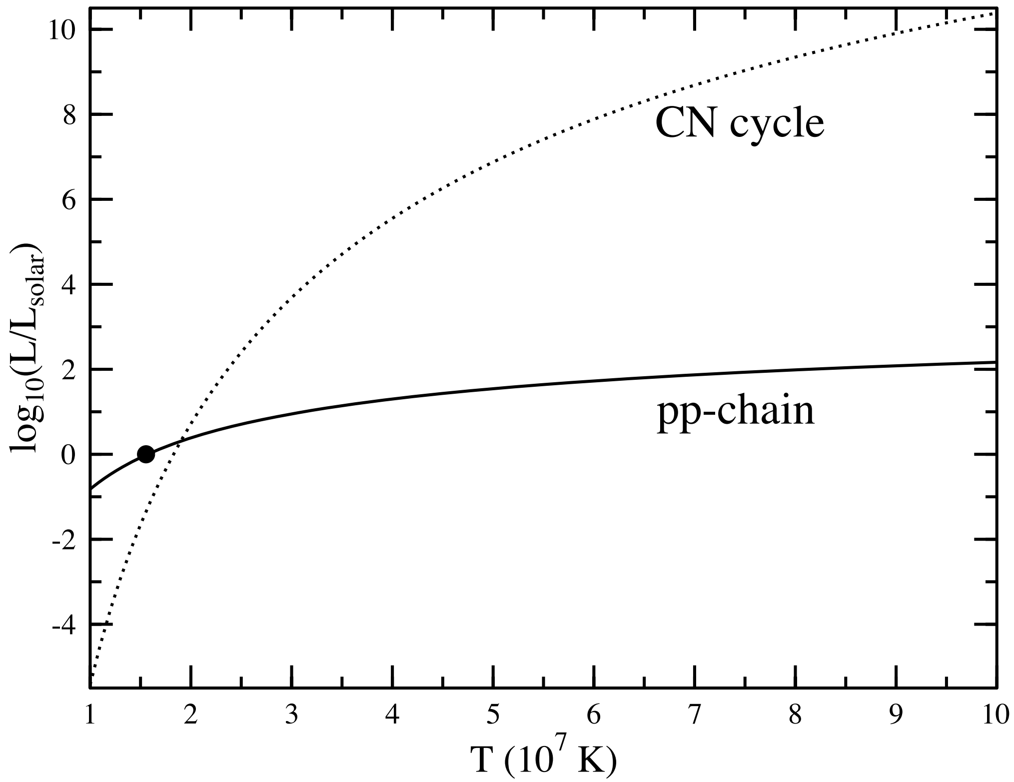
$${}^{7}Li + p \rightarrow 2\,{}^{4}He \qquad {}^{8}B \rightarrow {}^{8}Be^{*} + e^{+} \boxed{+ \nu_e}$$

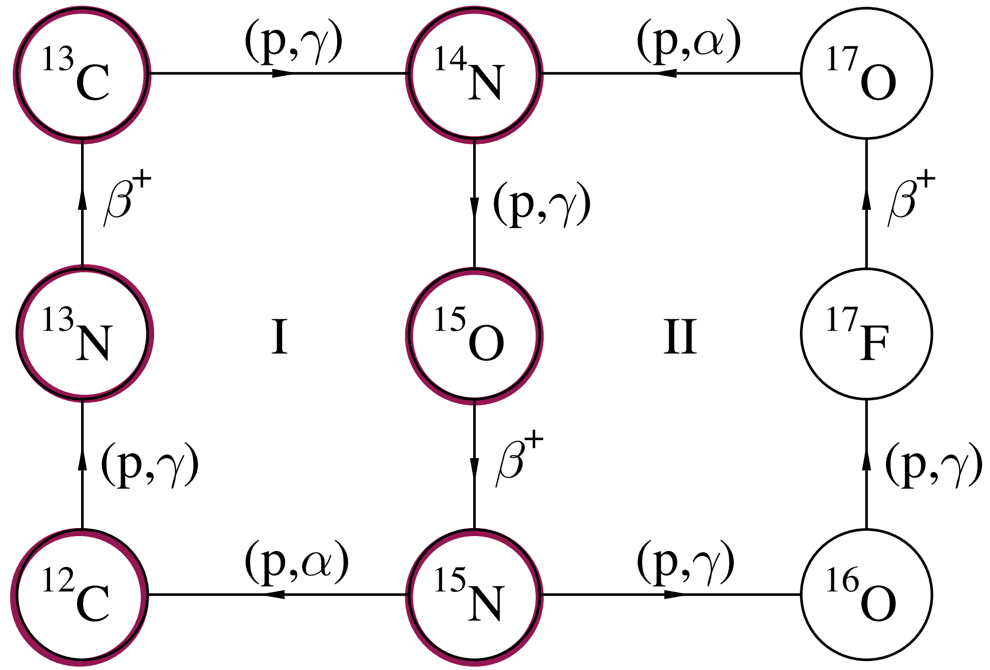
ppI ppII ppIII

Super-K and SNO measured

But Bethe showed that another way to burn H was needed

- A sharply T-dependent process for needed to sustain massive MS stars
- pp chain (primary) vs CN cycle (secondary): catalysts for CN cycle are pre-existing metals (except the very interesting case of the first stars)





- The CN-cycle contributes modestly to solar energy generation ~ 1%

- but produces measurable neutrino fluxes

$$^{13}\mathrm{N}(\beta^+)^{13}\mathrm{C} \quad E_\nu \lesssim 1.199 \text{ MeV} \quad \phi = (2.93^{+0.91}_{-0.82}) \times 10^8/\mathrm{cm}^2\mathrm{s}$$

$$^{15}\mathrm{O}(\beta^+)^{15}\mathrm{N} \quad E_\nu \lesssim 1.732 \text{ MeV} \quad \phi = (2.20^{+0.73}_{-0.63}) \times 10^8/\mathrm{cm}^2\mathrm{s}.$$

- these fluxes depend on the core temperature T, but also have an additional linear dependence on the total C+N in the Sun's core

$$\phi_\nu^{\mathrm{CN}} = F[S_{14}{}_{N+p}; \quad T; \quad \theta_{12}; \quad CN]$$

what we want to determine

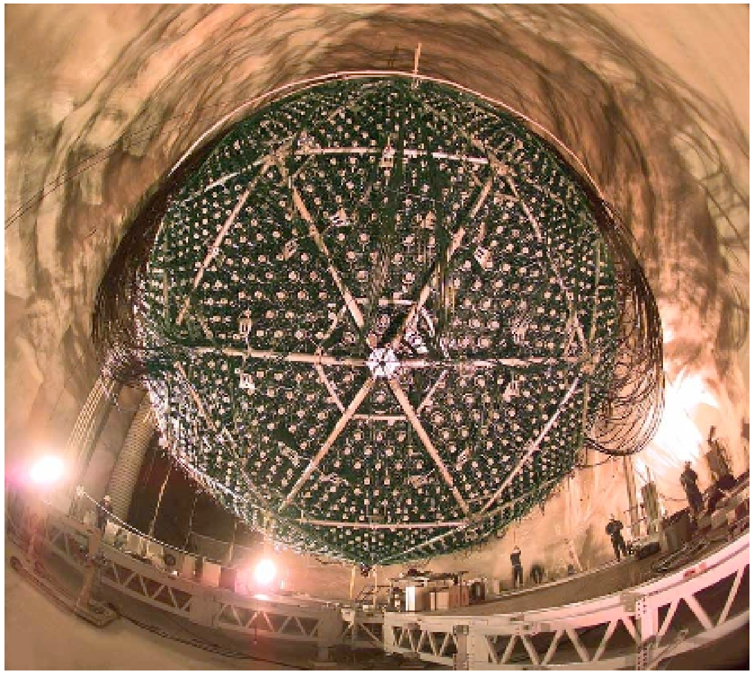
- The CN-cycle contributes modestly to solar energy generation ~ 1%
- but produces measurable neutrino fluxes

$$^{13}\mathrm{N}(\beta^+)^{13}\mathrm{C} \quad E_\nu \lesssim 1.199 \text{ MeV} \quad \phi = (2.93^{+0.91}_{-0.82}) \times 10^8/\mathrm{cm}^2\mathrm{s}$$

$$^{15}\mathrm{O}(\beta^+)^{15}\mathrm{N} \quad E_\nu \lesssim 1.732 \text{ MeV} \quad \phi = (2.20^{+0.73}_{-0.63}) \times 10^8/\mathrm{cm}^2\mathrm{s}.$$

- these fluxes depend on the core temperature T, but also have an additional linear dependence on the total C+N in the Sun's core

$$\phi_\nu^{\mathrm{CN}} = F[S_{14}{}_{N+p}; \quad T; \quad \underbrace{\theta_{12}}_{\text{well enough measured by SNO and KamLAND}}; \quad CN]$$



- The CN-cycle contributes modestly to solar energy generation ~ 1%
- but produces measurable neutrino fluxes

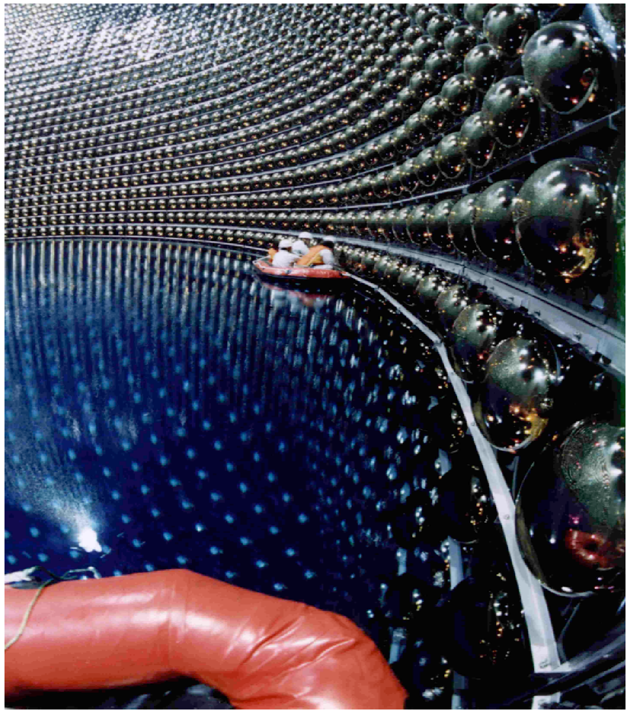
$$^{13}\mathrm{N}(\beta^+)^{13}\mathrm{C} \quad E_\nu \lesssim 1.199 \text{ MeV} \quad \phi = (2.93^{+0.91}_{-0.82}) \times 10^8/\mathrm{cm}^2\mathrm{s}$$

$$^{15}\mathrm{O}(\beta^+)^{15}\mathrm{N} \quad E_\nu \lesssim 1.732 \text{ MeV} \quad \phi = (2.20^{+0.73}_{-0.63}) \times 10^8/\mathrm{cm}^2\mathrm{s}.$$

- these fluxes depend on the core temperature T, but also have an additional linear dependence on the total C+N in the Sun's core

$$\phi_\nu^{\mathrm{CN}} = F[S_{14}{}_{N+p}; \quad T; \quad \theta_{12}; \quad CN]$$

calibrated to 0.5% by Super-Kamiokande



- The CN-cycle contributes modestly to solar energy generation ~ 1%
- but produces measurable neutrino fluxes

$$^{13}\mathrm{N}(\beta^+)^{13}\mathrm{C} \quad E_\nu \lesssim 1.199 \text{ MeV} \quad \phi = (2.93^{+0.91}_{-0.82}) \times 10^8/\mathrm{cm}^2\mathrm{s}$$

$$^{15}\mathrm{O}(\beta^+)^{15}\mathrm{N} \quad E_\nu \lesssim 1.732 \text{ MeV} \quad \phi = (2.20^{+0.73}_{-0.63}) \times 10^8/\mathrm{cm}^2\mathrm{s}.$$

- these fluxes depend on the core temperature T, but also have an additional linear dependence on the total C+N in the Sun's core

$$\phi_\nu^{\mathrm{CN}} = F[S_{14\,N+p}; \quad T; \quad \theta_{12}; \quad CN]$$

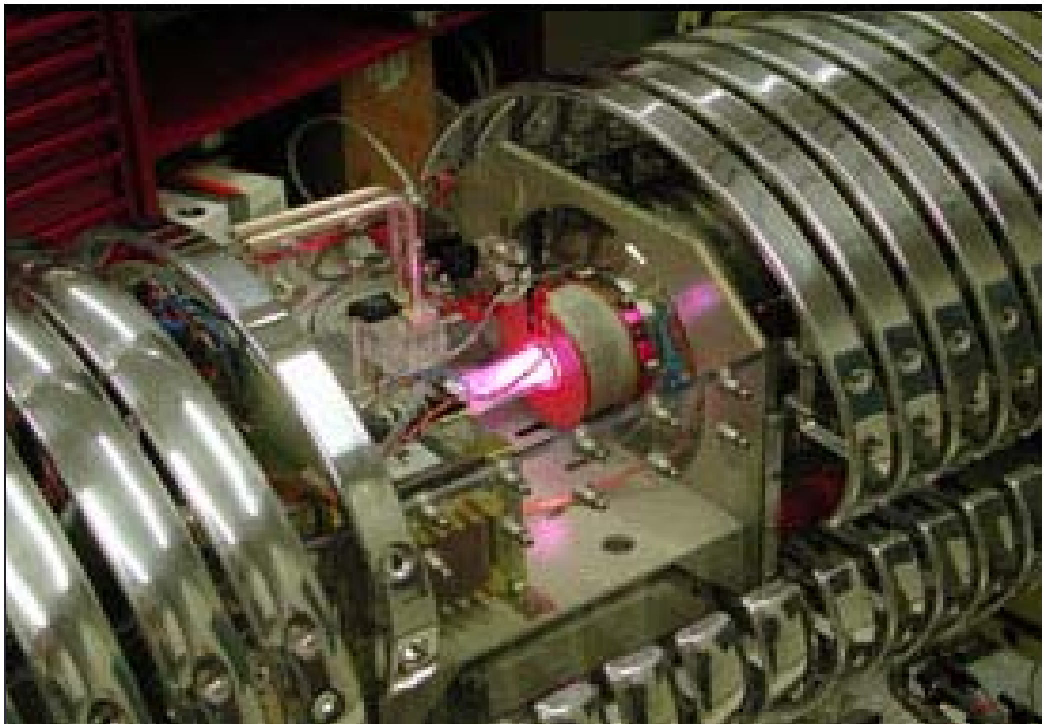
a significant problem until recently

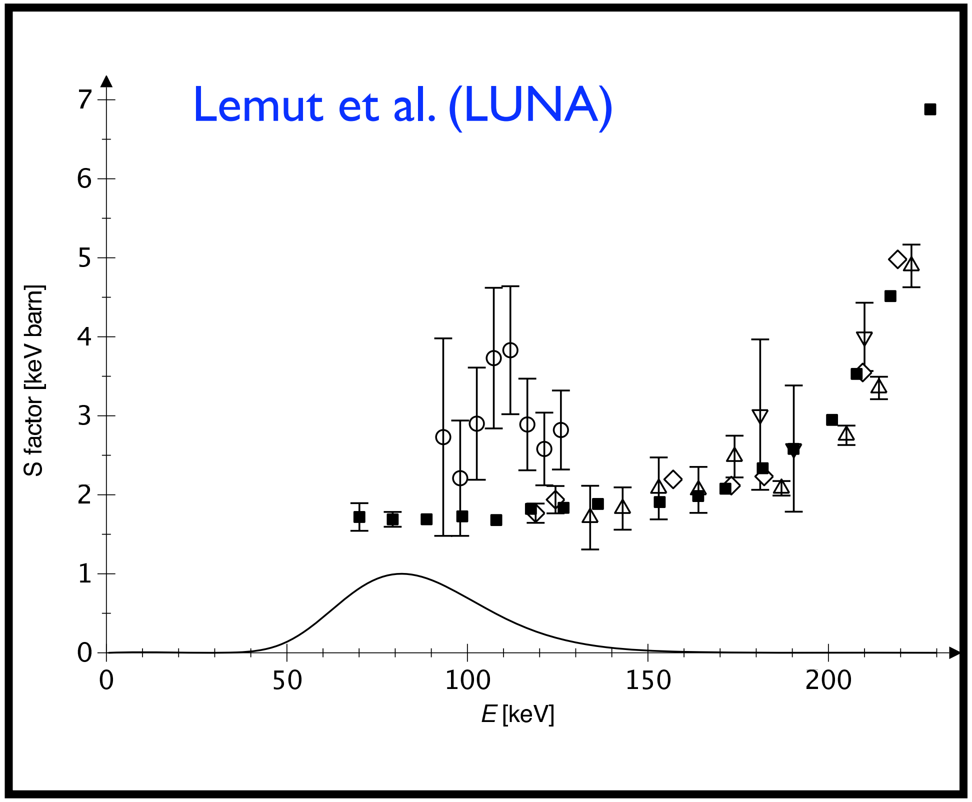
The nuclear physics is finally under control

LUNA and LENA measurements of ^{14}N(p,γ)

Formicola (LUNA) et al. (2004); Imbriani et al. (2005);
Bemmerer et al (2006); Lemut et al. (2006);
Trautvetter et al. (2008); Runkle (TUNL) et al. (2005)

S-factor mapped down to 70 keV





- The CN-cycle contributes modestly to solar energy generation ~ 1%
- but produces measurable neutrino fluxes

$$^{13}\mathrm{N}(\beta^+)^{13}\mathrm{C} \quad E_\nu \lesssim 1.199 \text{ MeV} \quad \phi = (2.93^{+0.91}_{-0.82}) \times 10^8/\mathrm{cm}^2\mathrm{s}$$

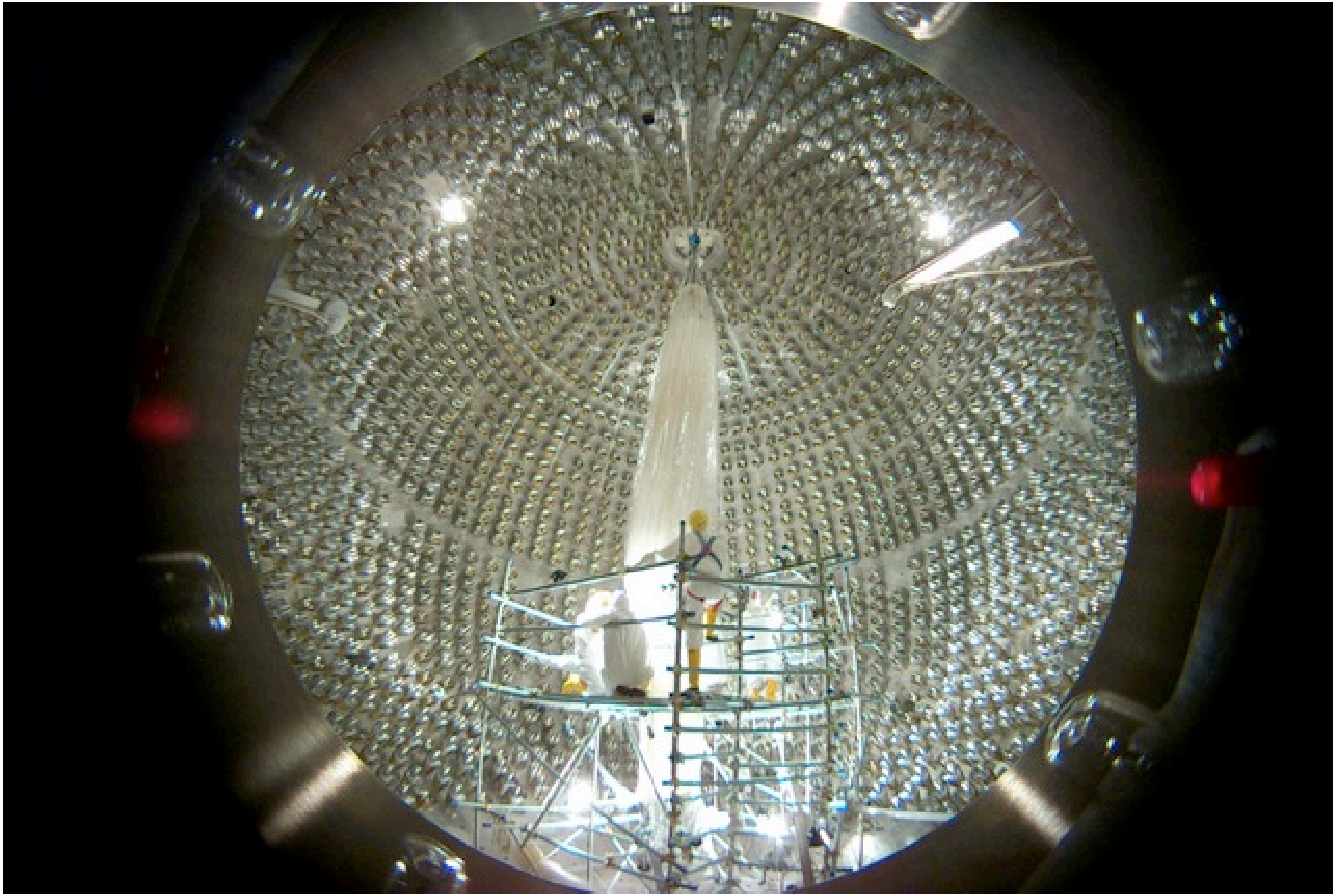
$$^{15}\mathrm{O}(\beta^+)^{15}\mathrm{N} \quad E_\nu \lesssim 1.732 \text{ MeV} \quad \phi = (2.20^{+0.73}_{-0.63}) \times 10^8/\mathrm{cm}^2\mathrm{s}.$$

- these fluxes depend on the core temperature T, but also have an additional linear dependence on the total C+N in the Sun's core

$$\phi_\nu^{\mathrm{CN}} = F[S_{14}{}_{N+p}; \quad T; \quad \theta_{12}; \quad CN]$$

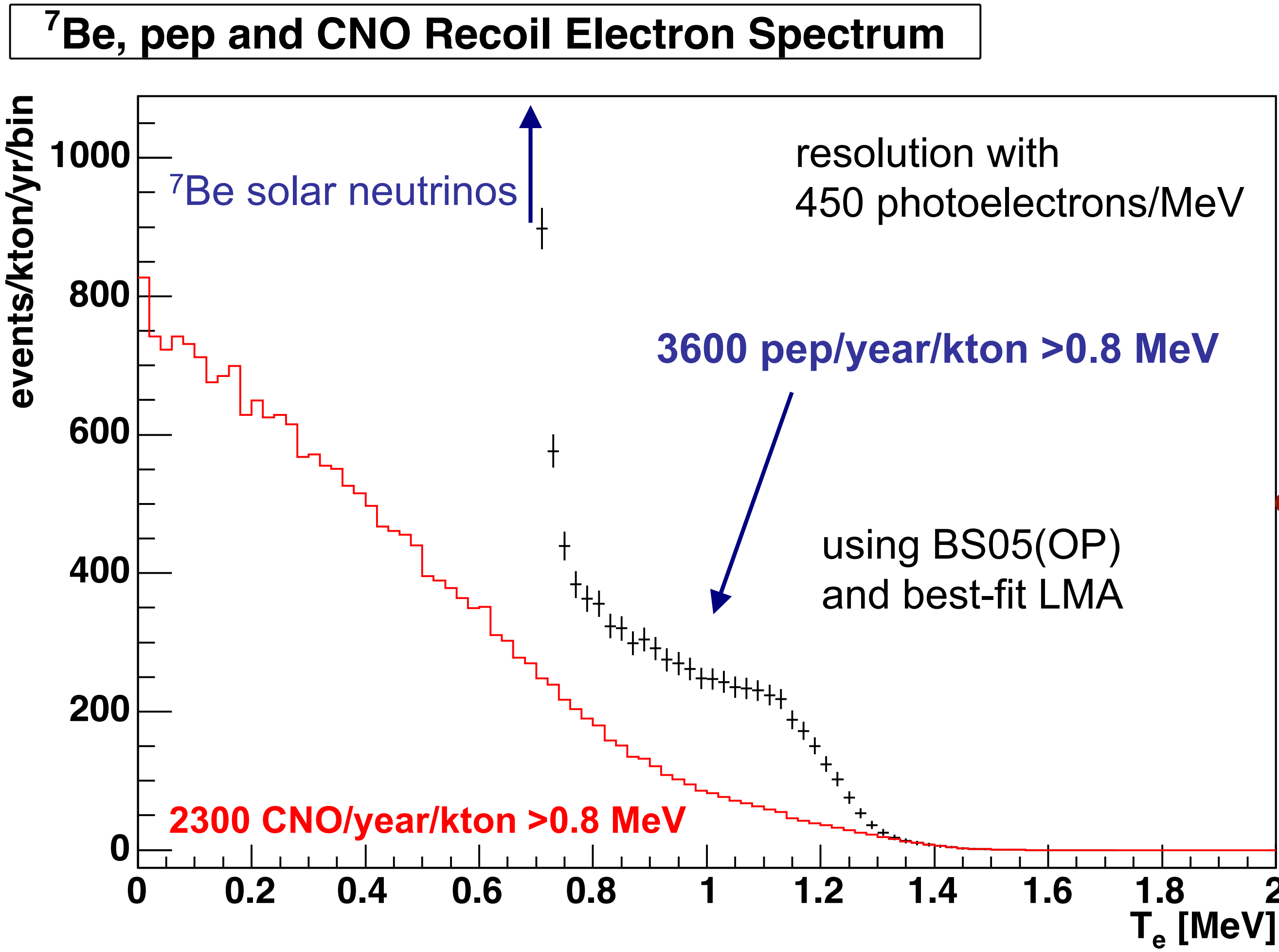
$$\big\downarrow$$

$$\boxed{\text{an experiment capable of measuring the fluxes}}$$



Borexino and KamLAND have developed the technology --
but one must be much deeper to avoid CR production of ^{11}C

SNO+: Borexino × 3 at SNOLab depts



(from Mark Chen)

A similar detector -- Borexino -- now operating at Gran Sasso, with exceptional low environmental radioativity rates

Assumes one kt scintillator at SNOLab depth: factor-of-70 reduction in long-lived cosmogenic ^{11}C, to 0.1 c/d/100 tons, relative to Borexino

10% CNO flux measurement predicted, based on BS05(OP) fluxes

Summary

- SSM has always depended on assumptions about pre-solar evolution -- important that we get this right

- the idea of a connection between planetary formation and solar structure is intriguing: there ought to be solar signatures today of the dilution process, captured in the helioseismology

- there could be important astronomical implications: is a star's anomalous metalicity an indicator of the likelihood of planets?

- the bottom line is that the solar neutrino program developed by nuclear physics may provide the one quantitative tool for proving that the Sun's core is metal rich, compared to surface

- with no further improvements, the CN core abundance could be determined to 14%

References

“CN cycle and solar metalicity,” W. Haxton and A. Serenelli   Ap J 687 (2008) 678

“Accurate abundancy patterns of solar twins and analogs,” Ramirez, Melendez, & Asplund, Astron. and Astroph. 508 (2009) L17

“Solar twins and possible solutions of the solar and Jupiter abundance problems,” A. Nordlund, Ap. J. Letts. (2010) (in press)

John Bahcall Fellow, IAS
now MPI Munich